JC² October 12, 13, 14, 2022

ONERA THE FRENCH AEROSPACE LAB

cnes CENTRE NATIONAL D'ÉTUDES SPATIALES

RÉPUBLIQUE FRANÇAISE Liberté Égalité Fraternité

Prediction of the unsteady pressure field in the transonic regime for space launchers using innovative methods

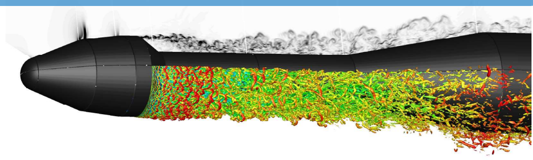
Simon Lecler[1] (simon.lecler@onera.fr), Pierre-Élie Weiss[1], Sébastien Deck[1]

1. ONERA, Aerodynamics, Aeroelasticity, Acoustics Department, Advanced Turbulence Modelling & Simulation Unit

Overview

General overview

- During atmospheric ascent, **space launchers** experience large dynamic loads at **transonic conditions.** ➔ Buffet loads are related to **the unsteady wall-pressure field.**
- Performing numerous unsteady CFD simulations remains expensive in terms of computational time and resources in the design phase.



(a): Instantaneous flow around a generic space launcher (NASA Model 11) computed with ZDES

State of the art of rapid prediction models

- **Semi-empirical** models (Corcos[1])
  ➔ Simple mathematical formulation that fits experimental data
- **Analytical** spectral models[2]
  ➔ Approximate solution of the Poisson equation governing pressure fluctuations

✓ Computationally efficient
✓ Mostly validated on Turbulent Boundary Layer flow
✗ Limited domain of application
✗ Not adapted to complex detached and 3D flows

Existing models cannot be applied on complex transonic flows around space launchers

Objectives

- Develop new models adapted to the **3D transonics flows** encountered around space launchers **with limited computational cost**
- Investigate the potential of **AI algorithms** to predict the pressure fluctuations in zones where analytical models fail based on databases generated with **ZDES**[3]

Pressure fluctuation models

New Analytical model

Development

Pressure fluctuations governed by a **Poisson equation**:

$$\frac{1}{\rho}\nabla^2 p' = \underbrace{-2\frac{\partial u_j}{\partial x_i}\frac{\partial U_i}{\partial x_j}}_{\text{turbulence-mean shear}} - \underbrace{\frac{\partial^2}{\partial x_i \partial x_j}\left(u_i' u_j' - \overline{u_i' u_j'}\right)}_{\text{turbulence-turbulence}}$$

Derivation of a 3D compressible Helmholtz equation:

$$\frac{\partial^2 \widehat{p'}(\boldsymbol{k},x_2)}{\partial^2_{x_2}} - \boldsymbol{k}^2 \widehat{p'}(\boldsymbol{k},x_2) = -2ik_i \frac{\partial \rho U_i}{\partial x_j}\widehat{u_j'}(\boldsymbol{k},x_2) - 2\frac{\partial \rho U_2}{\partial x_i}\frac{\partial \widehat{u_i'}}{\partial x_2}$$

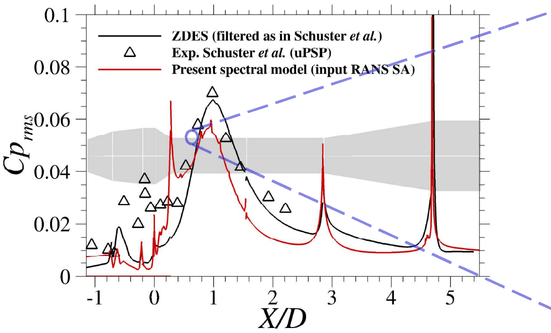
The following assumptions are adopted:

- Homogeneous turbulence in planes parallel to the wall
- Taylor's hypothesis of frozen turbulence
- Von Karman turbulence energy spectrum

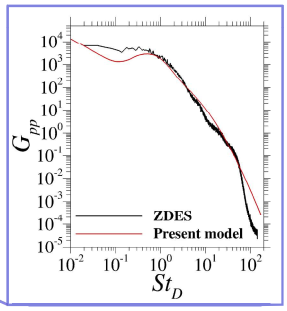
$$\phi_{pp}(\boldsymbol{k}) = \int_{\boldsymbol{k}'} \widehat{p'}(\boldsymbol{k},0)\overline{\widehat{p'}(\boldsymbol{k},0)}d\boldsymbol{k}' \quad \langle p^2 \rangle = \frac{1}{U_c}\int_0^\infty \int_{-\infty}^\infty \phi_{pp}\left(\frac{\omega}{U_c},k_3\right)dk_3 d\omega$$

Integrations performed using **Gaussian quadratures**

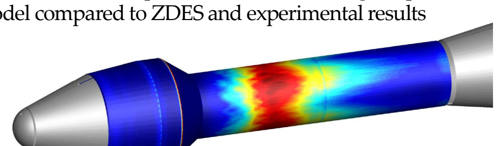
Application: NASA Model 11



(b): Predicted RMS pressure coefficient using the present model compared to ZDES and experimental results



(c): Predicted pressure spectrum compared to ZDES

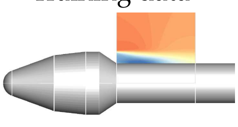


(d): Iso-contours of Cp_{rms} at the wall predicted by the present model

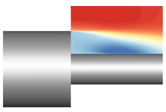
Data driven approach

Methodology

Training data

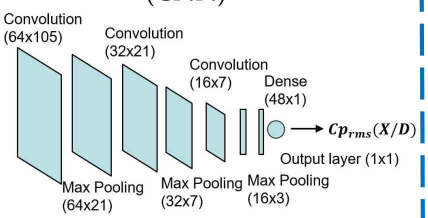


(e): Mean flow field of the first training configuration



(f): Mean flow field of the second training configuration

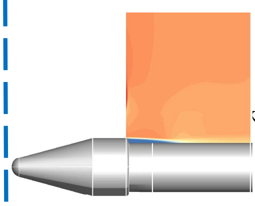
Convolutional Neural Network (CNN)



(g) Architecture of the trained 1D Convolutional Neural Network

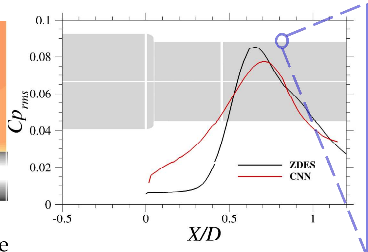
Application: NASA Model 13

Testing data

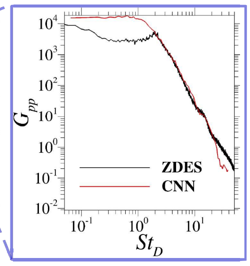


(h) Mean flow field of the testing configuration

Prediction



(i) Predicted Cp_{rms} compared to the ZDES data



(j) Predicted pressure spectrum compared to the ZDES data

Conclusion / Perspectives

✓ **Analytical model** successfully applied on a launcher configuration involving **attached and detached flow regions**
✓ Good agreement compared to ZDES data obtained only in **a few minutes**
➔ Application on a configuration with non-zero angle of attack
✓ The present **data-driven model** for separated/reattaching flows predicts pressure fluctuations for an **unseen configuration** on the basis of **only two training cases**
➔ Further development of the training database
➔ Hybridization of both analytical and data-driven approaches

Bibliography

[1] G. M. Corcos, " Resolution of Pressure in Turbulence ", J. Acoust. Soc. Am., 35 (2), pp. 192–199 (1963).
[2] G. Grasso, P. Jaiswal, H. Wu, S. Moreau, and M. Roger, "Analytical models of the wall-pressure spectrum under a turbulent boundary layer with adverse pressure gradient ", Journal of Fluid Mechanics 877, 1007–1062 (2019).
[3] S. Deck and N. Renard, " Towards an enhanced protection of attached boundary layers in hybrid RANS/LES methods ", Journal of Computational Physics 400 (2020).